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Indoor airborne particle sources and outdoor haze days effect in urban office areas in Guangzhou

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ABSTRACT

To identify the sources of $PM_{2.5}$ pollutants in work environments and determine whether the air quality inside an office was affected by a change in outdoor pollution status, concurrent indoor and outdoor measurements of $PM_{2.5}$ were conducted at five different office spaces in the urban center of Guangzhou on low pollution days (non-episode days, NEDs), and high pollution days (haze episode days, EDs). Indoor-outdoor relationships between the $PM_{2.5}$ mass and its chemical constituents, which included water-soluble ions, carbonaceous species, and metal elements, were investigated. A principle component analysis (PCA) was performed to further confirm the relationship between the indoor and outdoor $PM_{2.5}$ pollution.

The results reveal that (1) Printing and ETS (Environmental tobacco smoking) were found to be important office $PM_{2.5}$ sources and associated with the enrichment of SO_4^{2-}, OC, EC and some toxic metals indoors; (2) On EDs, serious outdoor pollution and higher air exchange rate greatly affected all studied office environments, masking the original differences of the indoor characteristics (3) Fresh air system could efficiently filter out most of the outside pollutants on both NEDs and EDs.

Overall, the results of our study suggest that improper human behavior is associated with the day-to-day generation of indoor $PM_{2.5}$ levels and sporadic outdoor pollution events can lead to poor indoor air quality in urban office environments. Moreover, fresh air system has been experimentally proved with data as an effective way to improve the air quality in office.

1. Introduction

Fine particle ($PM_{2.5}$) pollution is now identified as a major risk globally. Approximately 3.2 million instances of premature mortality have been attributed to the ambient $PM_{2.5}$ pollution in 2010 worldwide (Lim et al., 2013). Currently, due to the development of the economy and population, China and other developing countries are facing with an increasing air pollution burden. It has been reported that only 25 out of 190 cities in China were able to meet the National Ambient Air Quality Standards (NAAQS) (daily, 75 μg/m^3), and the population-weighted mean of $PM_{2.5}$ in China cities (61 μg/m^3) was approximately three times folds higher than the global value (20 μg/m^3) (Zhang and Cao, 2015). In 2014, one self-organized research institute, the Beijing City Lab (BCL), reported that 1322 million people, that is 98.6% of China's total population, were exposed to $PM_{2.5}$ at a level above the daily guideline of the WHO (25 μg/m^3) for more than half a year (Long et al., 2014). Beijing, Shanghai, Guangzhou and other large cities are suffering increasing occurrences of haze episodes in recent decades, events that are characterized by high $PM_{2.5}$ levels and low visibility (Zhang et al., 2014, 2015).

According to the forecasts of demographic and epidemiological transitions, average $PM_{2.5}$ levels would need to decrease approximately 20–30% over the next 15 years to offset the increase in mortality attributable to $PM_{2.5}$ levels among aging populations in China (Apte et al., 2015). However, most of the health risk assessment nowadays were based on outdoor air data. And the truth is that in general population, a large fraction of human exposure to $PM_{2.5}$ occurs indoors as people spend 60–80% on average of their lifetime indoors (Klepeis et al., 2001). This fraction includes approximately 8 h a day in office for most urban citizens. Therefore, more recent studies have focused on indoor $PM_{2.5}$ pollution in order to better assess human exposure to $PM_{2.5}$. Nevertheless, most of the studies to date have focused on residential buildings. There are only few reports that evaluate the air quality in office (Dong et al., 2013; Lim et al., 2011; Sangiorgi et al., 2013; Tang et al., 2012). These previous studies have found that some office electronic equipment, including computers, multifunctional

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office machines, air conditioners, and particularly photocopiers and printers, were sources of $PM_{2.5}$ inside office (He et al., 2007; Koivisto et al., 2010; Wensing et al., 2008). Although smoking has been strictly prohibited in most public indoor areas in urban China, there is no legislative regulation regarding smoking in private offices. Therefore, smoking may be an important $PM_{2.5}$ contributor in offices. Moreover, the sick building syndrome (SBS) is a well-known, work-related health effect with symptoms that include a headache, fatigue and difficulty concentrating. Zamani et al. (2013) reported that SBS symptoms were significantly associated with high levels of indoor air pollutants, including $PM_{2.5}$. Thus, with regard to human health and the efficiency of office workers, the indoor air quality of offices requires much more attention. Another important global risk factor that demands increased research and policy-making endeavors, is the indoor air pollution that originates from outdoor air pollution (Bruce et al., 2000).

Primarily, it is important to determine whether the air quality inside an office is affected by the changes in outdoor air conditions and to identify the sources of pollutants within the work environment. Here, we chose to investigate five different types of office environments in Guangzhou. This study was designed to investigate the physical (i.e., mass concentration) and chemical (i.e., water-soluble ions, carbon species and metals) differences between indoor and outdoor $PM_{2.5}$ on both high (EDs) and low pollution event days (NEDs) in urban offices, aiming to find out the inner source of PM2.5 pollution inside office. A principle component analysis was used to identify the $PM_{2.5}$ sources in these office spaces during two sampling campaigns (EDs and NEDs). According to a previous report from Guangzhou (Tao et al., 2009), the threshold $PM_{2.5}$ value on EDs for this study was set at 100 $\mu g/m^3$.

2. Experimental

2.1. Sampling location

Guangzhou is the largest city in South China. The Tianhe district is the fastest-developing area, known as the new urban center in Guangzhou. Our sampling was performed in one office building located there, approximately 300 m away from the District Government. Five offices in the same building with different indoor conditions were selected for this study. Briefly, office #1 (a single-user office, SO) was a small office occupied by only one person and had no obvious $PM_{2.5}$ emission inner sources. Office #2 (a multi-user office, MO) was a larger office shared by seven people and had one printer that was occasionally used. Office #3 (a photocopy room, PC) was a photocopy room with three printers that worked constantly during the whole day. Office #4 (an ETS office, EO) was an ETS (environmental tobacco smoking) office where three workers frequently engaged in smoking activities and the cigarette consumption was estimated to be over 30 per day. Office #5 (a fresh air office, FO) had no $PM_{2.5}$ sources and had an advanced fresh air system. Here, we consider the single-user office, multi-user office and fresh air office as the common offices, while the other two types were investigated to identify the potential office PM sources. Brief information on sampling sites is shown in Table S1. The outdoor sampling site was located on the roof of the selected office building, approximately 32 m above ground level.

2.2. Sampling methodology

$PM_{2.5}$ was collected simultaneously at the indoor and outdoor sites, from March 1–8, 2015 (EDs) and June 14–21, 2015 (NEDs), by intelligent $PM_{2.5}$ samplers (TH-150C, Wuhan Tianhong Corporation, Wuhan, China). The samplers were set at a flow rate of 100 L/min for 24 h. Before and after sampling, the sampler air flow rates were calibrated. To simulate the breath zone and to avoid potential interference from dust resuspension, the sampling heights were approximately 1.2 m above the ground. Quartz microfiber filters (QMA, D90 mm, Whatman Ltd, USA.) were used for particle collection. Prior to sampling, blank filters were baked at 450 ℃ for at least 4 h. After equilibration for at least 24 h in a desiccator at room temperature (22 ℃), the filters were weighed on an electronic microbalance with a 0.1 mg sensitivity (Sartorius, CPA 225D, Germany).

2.3. Chemical analysis

2.3.1. Water-soluble ions (WSIs)

Both cations and anions in the aqueous extracts from a portion of the sample filter (1.33 cm^2) were identified with a Dionex-3000 Ion Chromatograph (Dionex Inc., Sunnyvale, CA, USA). For the cation analysis (Na^+, NH_4^+, K^+, and Ca^{2+}), the instrument was equipped with an IonPac CS12A column and a CG12A guard column. For the anion analysis (Cl^-, NO_3^- and SO_4^{2-}), an IonPac AS11-HC and an AG11-HC guard column were used.

2.3.2. Carbon species (OC/EC)

Following the IMPROVE-A (Interagency Monitoring of Protected Visual Environments) thermal/optical reflectance (TOR) protocol, a quarter of each sample filter was analyzed for eight carbon fractions using a thermal and optical carbon analyzer (DRI Model 2001, Atmoslytic Inc., USA).

2.3.3. Metal elements (MEs)

A quarter of each quartz filter was used for metal analysis. Fourteen metal element species (Pb, Al, Ba, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Se, Cd, and Sb) were determined using an Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and one metal element (As) was determined using atomic fluorescence spectrometry (AFS).

2.4. Data analysis

Seven samples from each sample site taken on either a NEDs or an EDs were considered to be a single case. In total, 84 filter samples were obtained. One blank and one duplicate sample were included in each batch (10–12 samples) during the chemical analysis. The duplicate sample was chosen randomly for each batch. The final sample concentration was obtained after subtracting the corresponding blank value. The concentrations that fell beneath the detection limit were set to be half of the detection limit. The detection limits for the three groups of chemical components are listed in Table S2. Only the component values for which the detection rates were above 50% were considered valid. Statistical calculations in this study were performed using IBM SPSS statistics version 19.0, and a principal component analysis was performed using SIMCA-P version 13.0 (Umetrics, Umeå, Sweden).

The PCA was performed to compare the chemical component profiles of the multiple indoor spaces with the outdoor environment. The values of all WSIs, OC, EC and metal elements from each sample were used in the PCA, except for the elements that had a detection rate less than 50% (i.e., Ba, Ni and Cd on NEDs). The data were first normalized and a PCA-X was performed for an overview of the data. This process allowed us to identify the relationships between the indoor and outdoor $PM_{2.5}$ levels on either NEDs or EDs based on the group characteristics and distances in the resulting plots.

3. Results and discussion

3.1. Fine particle mass concentrations

Table 1 summarizes the variations in the fine particle mass of indoor and outdoor sites on low and high pollution event days. The average outdoor $PM_{2.5}$ concentrations on EDs (161 ± 37.5 $\mu g/m^3$) were more than two times higher than that on NEDs (71.7 ± 12.4 $\mu g/m^3$), and the phase data were significantly different (99% confidence level). Similar to the outdoor environment, significantly increased $PM_{2.5}$